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Authored	Ken Rhinefrank		
Reviewed	Brad Lamb, Reenst Lesemann		
Approved	Reenst Lesemann		
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1 PURPOSE

This document summarizes the Columbia Power Technologies (CPower) System Performance Assessment (SPA) and LCOE goals and projections under DE-EE0006399 (Project LandRAY) for the latest StingRAY wave energy converter (WEC) design. To determine Project goal achievement, three power take off (PTO) configurations—the baseline geared PTO module (GP1), the actual Project direct-drive PTO module (DDP1) and the next-generation direct-drive PTO module (DDPx)—and associated costs are compared using the StingRAY v3.2 WEC design. The DDP1 WEC model (DDS1) and the DDPx WEC model (DDSx) are compared against the baseline GP1 WEC (GS1) to determine Project success. A forward-looking LCOE assessment will be made at the end of the Project using DDPx, which incorporates Project learning.

To understand progress during the Project, separate time-domain models will be run on DDS1, reflecting the current knowledge and understanding of the DDP1 PTO at three Project stages: pre-Project (DDS1-p), intermediate–Project (DDS1-i) and final (DDS1-f). These three Project-stage models of the DDS1 WEC will be assessed, in order to gauge the improvement of SPA and LCOE as a function of Project performance, i.e., validated improvements of the CPower PTO design.

2 SYSTEM ASSESSMENTS

To accurately assess LCOE and SPA goals and to follow DOE request, the Project metric analysis and comparisons are driven by the five different PTO design models—baseline geared (GS1), three direct-drive models (DDS1-p, DDS1-i & DDS1-f) and the next generation model (DDSx)—although all use a common WEC design. Annual Energy Production (AEP) computations require time-domain model results at each of these assessment stages. The StingRAY v3.2 WEC has developed substantially since the Project was originally proposed, and running computationally-intensive time-domain AEP models on the most recent StingRAY WEC design (as opposed to a two-year-old design) is the only avenue that provides useful forward-looking LCOE information to both CPower and DOE. Project proposal and SOPO LCOE and PWR calculations used AEP calculations that assumed a learning curve and associated performance gains for a 2020 WEC array after product development experience and the associated increase in AEP. However as explained below, only quantified improvements are included.

DDS1-f and DDSx are the systems which target the Project SPA and LCOE goals. Due to NWTC size constraints and budget limitations, the LandRAY test article is scaled down in diameter, torque and nameplate rating from the DDS1 system. All SPA and LCOE calculations use a DDR PMG that is full size and rating.

2.1 System Definitions

The five assessment models are defined as follows and are mapped in section 2.1.6 for alignment with the SOPO systems.

2.1.1 GS1

The GS1 WEC system employs a gearbox to step up rotational speed of the permanent magnet generator (PMG). The efficiency, mass, inertia and cost of the gearbox-based PTO are used in the GS1 WEC assessment. This is the baseline system to be compared against the new PTO improvements and learning. Time-domain models will not be run on this device, to avoid unproductive use of modeling resources. Instead, GP1 efficiencies will be applied to the performance of the DDS1-p system.

2.1.2 DDS1-p

This is the DDS1 WEC design with the direct-drive PTO DDP1 as understood prior to Project commencement. The DDS1-p WEC uses a forecasted performance model of the pre-Project direct-drive rotary (DDR) PMG. The efficiency, mass, inertia, availability and cost of the pre-Project DDP1 are used in the DDS1-p WEC assessment.

2.1.3 DDS1-i

This is the DDS1 WEC design with the DDP1 PTO as designed, manufactured and understood at the Go/No-Go (GNG) decision point. The intermediate-stage DDS1-i WEC uses a more-accurate forecasted model of the PTO that incorporates the latest information available at the time of GNG Project assessment. The efficiency, mass, inertia, availability and cost as understood at the GNG are used in the DDS1-i WEC assessment. DDS1-i performance is used for comparison against GS1 and DDS1-p.

2.1.4 DDS1-f

This is the DDS1 WEC with the DDP1 PTO as designed, manufactured, built and tested. The final-stage DDS1-f WEC uses the most-accurate forecasted performance model of the DDP1 information, with the latest experimental information available at the close of the Project. The efficiency, mass, inertia, availability and cost as understood at the final-stage of the Project are used in the DDS1-f WEC assessment. DDS1-f performance is used for comparison against GS1, DDS1-p and DDS1-i.

2.1.5 DDSx

This is the DDSx WEC with the next-generation direct-drive PTO as envisioned as a result of the Project effort. An improved PTO will be proposed using likely design improvements, identified during the Project as a function of Project learning. The efficiency, mass, inertia, availability and cost of the improved PTO will be used in the DDSx WEC assessment. DDSx performance is used for comparison against GS1, DDS1-p, DDS1-i and DDS1-f.

2.1.6 System Definitions mapping to SOPO

Table 1: System Configuration Table

System - configuration	PTO Configuration	Project Stage	Model Assessment Identifier	System Notes
GS1	GP1	Pre-Project	GS1	Baseline PTO, Modified DDS1-p WEC model is used and has more PTO mass and higher CG
DDS1	DDP1	Pre-Project	DDS1-p	PMG Prior to Project start
DDS1	DDP1	GNG	DDS1-i	Incorporates latest understanding of DDP1 at GNG
DDS1	DDP1	Post-Test	DDS1-f	Incorporates latest understanding of DDP1 post-Test
DDSx	DDPx	Post-Test	DDSx	Incorporates all knowledge gained for next-generation DDPx

3 SPA GOAL

The PTO Module has inherent capacity to demonstrate material improvements against baseline measurements for both System Performance Advancement (SPA) Goals – Power-to-Weight Ratio (PWR) and Availability – in addition to substantial LCOE reductions. ColPwr expects to reduce PWR and LCOE by approximately 80% each and to increase Availability by 18% through successful implementation of the PTO Module.

The following tables are from the SOPO:

Table 2. Baseline and Target Component Metric Values and Anticipated Project Metric Improvement (Single PTO)

Metric	PTO Module GP1	DDP1	DDPx	Project Improvement GP1-DDP1
Mass (tons)	67	35	53	48%
CAPEX (,000's)	$1,868	$1,452	$784	22%
Efficiency	66%	77%	85%	17%
Avg Annual Power (kW)	47	60	152	29%
Availability	83%	91%	98%	11%

Table 3. Baseline and Targeted Systems Goal Values

System Configuration	SPA Goals PWR (kW/mT)	Availability	LCOE ($/kWh)	
GS1 (Baseline)	0.26	83%	$0.91	10MW project using 2020 costs (ex-CAPEX)
DDS1 (Target 1)	0.41	91%	$0.66	10MW project using 2020 costs (ex-CAPEX)
DDSx (Target 2)	0.47	98%	$0.18	50MW project using 2020 costs (ex-CAPEX)

GS1: Baseline WEC for Metric comparison that uses the GP1 PTO
DDS1: Assumes 10MW project after 25MW has been installed
DDSx: Assumes a 25 MW project after 75 MW has been installed.

Table 4. Targeted System Improvements

Baseline-Target	Improvement Goal PWR	Availability	LCOE
GS1-DDS1	55%	10%	-28%
GS1-DDSx	78%	18%	-80%

Further detail on the Targeted Systems Improvements is contained within the original proposal:

"… the LCOE figures for all systems are based on an Oregon wave resource and not the DOE model wave resource."

To more closely conform to DOE guidance, annual array output is set to 260,000 MWh/yr versus the project size described in Table 3 and metrics are also provided for the DOE Reference Site of Humboldt, CA.

4 LCOE MODEL

Except where noted, the LCOE model used in this analysis is compliant with DOE Guidelines, as outlined in "doe_lcoe_reporting_guidance_2015_10_09.docx and NREL's 2011 Cost of Wind Energy Review.[1,2]

$$LCOE = ((ICC\ xFCR) + AOE) \div (AEP_{net} \div 1{,}000)$$

The LCOE model components are described below. The assumptions used in the model are discussed in Section 6.

4.1 Annual energy production (AEP)

AEP computation methodology is in accordance with DOE Guidelines, except some variance in approach is taken for efficient use of modeling resources. This variance is fully explained in Attachment 1.

The analysis within this Report contains data for both the Humboldt, CA DOE Reference Site and for Stonewall Bank, OR, which was used in the original proposal analysis. Humboldt has a less desirable spectrum of waves that is sub-optimal for wave energy due to long periods and shorter waves as compared to Stonewall Bank and numerous other more favorable sites.

[1] http://en.openei.org/community/document/mhk-lcoe-reporting-guidance-draft
[2] http://www.nrel.gov/docs/fy13osti/56266.pdf

To establish the initial pre-Project AEP on the DDS1-p WEC, CPower will perform time-domain modeling. For the GS1 system, CPower will use assumptions on efficiency and availability to estimate its TAEP, but will not use time-domain models on system GS1. TAEP calculation details are reviewed in Attachment 1, and TAEP results are included in Attachments 3, 4 and 5. AEP is computed from TAEP as follows:

$$AEP = TAEP \times (availability) \times (Trasmission\ efficiency)$$

AEP_{net}, which is used in the LCOE model, is expressed as MWh/MW/yr.

4.2 Installed capital Costs (ICC)

CPower has historically employed an alternative hierarchy to certain elements of the Draft Generalized Cost Breakdown Structure (CBS) for MHK Projects dated August 1, 2014.[3] CPower's hierarchy follows a more traditional naval architecture structure and includes the device and all components upstream of the sea-floor umbilical interface as part of the WEC. The Balance of System includes all components downstream of the interface through to the grid interconnect. CPower has integrated its hierarchy into the 2nd level of the DOE's CBS (Alternative CBS). A high-level view of this Alternative CBS is shown in Figure 1; greater detail is available in Attachment 2 (DDS1-p-BOM Master.xlsm).

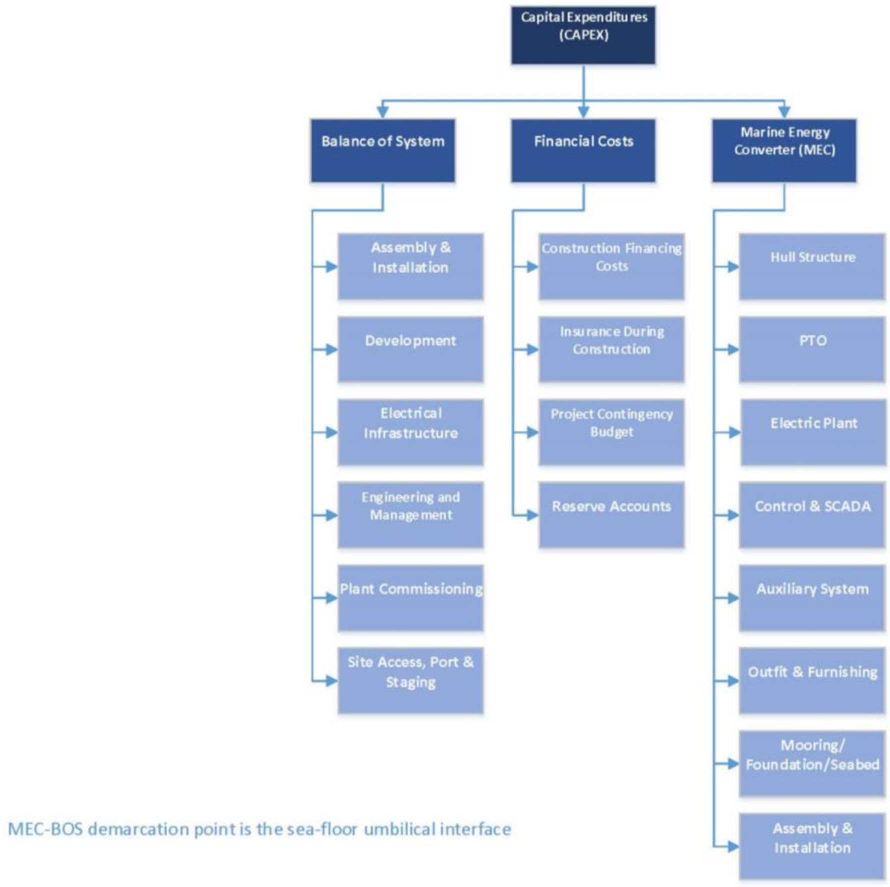

Figure 1: Alternative CBS

Aside from the differing segmentation described in this Section, ICC is calculated per DOE and NREL guidance. ICC is expressed as $/kW within the model.

[3] http://en.openei.org/community/document/mhk-cost-breakdown-structure-draft

4.3 Annual Operating Expense (AOE)

AOE is expressed as $/kW/yr and is calculated per DOE and NREL guidance.

4.4 Fixed Charge Rate (FCR)

The FCR is calculated to be 10.8% and is calculated per DOE and NREL guidance.

5 SPA GOAL APPROACH

5.1 PWR - SPA Goal 1

From the DOE, PWR guidance under FOA 848:

"Power to Weight Ratio (PWR) is defined as the ratio of effective power to weight in air of the device (see eqn. below). Improvement in PWR can be achieved by increasing the energy capture and conversion efficiency of the device or by reducing its weight. PWR drives cost throughout the life cycle, impacting device capital cost, handling equipment size and cost, difficulty of installation, deployment, and recovery. Applicants must quantify baseline system PWR value, and the target system PWR value for a single system that can be achieved via component technology innovations developed in this FOA."

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

Where,

- *Rated Capacity (kW) is the expected power that the system is designed to produce.*
- *Capacity factor is a ratio of the actual power produced at a site to the power produced by the device if operating at rated capacity, over a given time (typically one year).*
  - *Capacity factor used for both the baseline and target values shall be for the same site and assumed resource.*
- *Weight in Air (metric tons)*
  - *Includes all weight that impacts logistics and handling*
  - *Does not include weight of cables, moorings, or any other components assembled on-site.*
  - *Permanent ballast is included.*

PWR will be computed according to the above equation using AEP and both Active mass and Dry mass for the 2020 WECs. To achieve these DOE objectives and an additional alternative, the following approaches will be used:

5.1.1 Power

The 2020 WEC is assessed for AEP at each site using the approach discussed in section 4.2. From this AEP calculation and data, the following will be extracted:

$$Rated\ Capacity\ (kW) = Maximum\ average\ power\ delivered\ to\ grid\ over\ a\ ten\ minute\ period$$

$$Capacity\ Factor = \frac{site\ specific\ AEP}{8760\ hours\ x\ Rated\ Capacity}$$

$$PTO\ efficiency\ (at\ Rated\ Capacity) = \frac{Rated\ Capacity}{rated\ shaft\ input\ power}$$

5.1.2 Active mass (metric tons)

Total WEC mass included all necessary structural hardware and equipment from the WEC-side mooring attachment, but excluding water ballast and fixed ballast. This will be used to compute Active PWR.

5.1.3 Dry mass (metric tons)

Total WEC mass included all necessary structural hardware and equipment from the WEC-side mooring attachment, including fixed ballast, but excluding water ballast. This will be used to compute Dry PWR.

5.1.4 Displacement (metric tons)

Provided for reference, this is the Total WEC mass including all necessary structural hardware and equipment from the WEC-side mooring attachment, including fixed ballast and water ballast. Each WEC time-domain analysis uses the same WEC structure, the total displacement of each WEC model must be equal in order to keep the same WEC waterline (elevation in the water column). Variations in PTO mass are accounted for by adding or removing fixed ballast to keep displacement equal for all models.

5.2 PTO Availability - SPA Goal 2

No deviation from the DOE approach is expected. From the DOE, PWR guidance under FOA 848:

"Availability is the percentage of time a system is operable over the service life of the system (see equation below). Availability encompasses factors of reliability such as Mean Time Between Failure (MTBF), time to repair, and planned maintenance. Therefore, achieving a high availability percentage along with reduced number of maintenance visits per year results in lower LCOE through 1) an increase in the system's annual delivered energy; and 2) overall reduced Operations & Maintenance (O&M) cost of the MHK system through reduced component repair and replacement costs, and reduced logistic and labor costs associated with mobilizing vessels and crews to perform maintenance. Applicants must define their baseline and target availability for a single system, and planned and unplanned maintenance visits per year that can be achieved via component technology innovations developed in this FOA.

$$Availability = \frac{Operable\ Time}{Operable\ Time + Down\ Time}$$

$$Availability = \frac{Service\ Life - Down\ Time}{Service\ Life}$$

Where,

- *Operable Time = Service Life – Down Time*
- *Down Time should at a minimum take into consideration:*
    - *Mean Time Between Failures (MTBF) of critical components*
    - *Number of maintenance visits per year (planned and unplanned)*
    - *Weather windows for maintenance visits*
    - *Time to retrieve and redeploy the system*
    - *Mean Time To Repair (MTTR) of critical components"*

5.2.1 Component Service life

The component service life is defined as the median time period for which critical components are designed to be serviced. Critical components are those considered to be at risk of failure over the WEC service life. This applies to all systems, sub systems, support equipment and vessels required for support. The PTO is designed for a 20 year life, but some components have a shorter service limits.

5.2.2 WEC Service life

The WEC service life is defined as the design life of the WEC before major overhaul or decommissioning. The WEC is designed for a 20 year life, but some components have a shorter service life. To normalize different component lives, down time will be adjusted to the WEC service life as appropriate.

5.2.3 MTBF

Mean Time Between Failures (MTBF) of each critical component is component service life divided by the number of failures.

$$\text{Componenet MTBF} = \frac{component\ service\ life}{number\ of\ component\ failures}$$

5.2.4 MTTR

Mean Time To Repair (MTTR) is a component specific parameter for each critical component. MTTR is the total corrective maintenance time for a single component and does not include WEC retrieval and redeployment times, those are included when computing total WEC downtime.

5.2.5 Component Down Time (CDT)

Each critical component CDT is computed individually in the referenced spread sheets DDS1-p MTBF MTTR Service life PTO V2.xlsx for the entire service life. Component service life may be different from WEC service life and overall downtime is scaled accordingly.

$$CDT = \frac{WEC\ Service\ life}{component\ sevice\ life} \times \text{number of component failures} \times \text{MTTR}$$

5.2.6 System Down Time (SDT)

Sub system down times (SDT) are computed individually in the referenced spread sheets *DDS1-p MTBF MTTR Service life PTO V2.xlsx*.

$$SDT = \text{number of components} \times \text{CDT}$$

5.2.7 Down Time (DT)

DT is the total projected system downtime during the WEC service life and is the summation of all SDT's. That is to say, all down time from all components and sub systems during the service life is summed and reported as total down time (DT). A summation of DT for each subsystem is totaled in DDS1-p MTBF MTTR Service life PTO V2.xlsx and includes a time estimate for WEC Recovery and Deployment Time (RDT). RDT assumes a fixed time for recovery, refit and deployment and is added to all other component down times, thus a more extended repair period is included in DT; the five year recovery allows for planned refit of components that have a five year service live. It is initially assumed that a five year period between recovery and deployment will be planned and this will be adjusted once more operational data is collected. If calculated RecoveryEvents are more than five per year, it is assumed that refit is performed during those recoveries. If RecoveryEvents drop below once in five years, the DT will be adjusted to once in five years unless data supports otherwise.

$$DT = \sum_{k=0}^{n} CDT_k + (RecoveryEvents \times RDT)$$

$$\text{where; n} = \text{every critical component}$$

$$RecoveryEvents = Ceiling\left[\frac{\sum_{k=0}^{n} CDT_k}{AverageMTTR}\right]$$

where; $AverageMTTR =$ Average of all component MTTR's

Table 5: Down Time (DT) and Availability

System - configuration	DT (hours)	Service life (20yr*8760hr)	Availability (%)
GS1	29,784	175,200 hr	83
DDS1-p	13,201	175,200 hr	92.5
DDS1-i	13,201	175,200 hr	92.5
DDS1-f	-	175,200 hr	-
DDSx	-	175,200 hr	-

6 LCOE MODEL ASSUMPTIONS

To conform to the 2020 deployment scenarios for DDS1 and DDSx outlined in Section 3, all assessment models are adjusted to reflect the expected performance and CAPEX levels of a 2020 WEC.

The following high-level assumptions direct the approach for SPA and LCOE reporting:

6.1 WEC Capital Costs

Capital costs for the GS1, DDS1 and DDSx prototypes are shown in Table 6. The costs for all three WEC models are the same except for the PTO. The GP1 PTO, which is 138% heavier than DDP1, is estimated to cost 22% more than DDP1.

Experience curves are applied to the first prototype capital costs to determine 2020 WEC costs. The improvement rate calculations are done in accordance with National Energy Technology Laboratory (NETL) guidelines as referenced in the DOE guidance. To calculate the production unit number for determining the aggregate improvement, i.e., how far down the experience curve, the 2020 scenarios' previously installed capacity of either 25MW or 50MW plus 50% of the scenario's array capacity is divided by name plate capacity. For the GS1 and DDS1 calculations, this is the 81st unit (30MW/370kW).

Table 6 shows the experience curve rate assumptions and effect on capital costs. The rates are assigned to each sub-system grouping based on CPower estimate as to the potential savings available over time. All are within the 1-12% range discussed in DOE LCOE guidance, except for structure. The latest models for the next StingRAY design v3.3 suggest an experience rate above 15%. This is due to reduced use of FRP in the hull structure and ballast material substitution. StingRAY v3.2 uses steel ballast, while v3.3 will use concrete and seawater. The projected mass decrease from v3.2 to v3.3 is 64%. Assuming that mass is a valid proxy for cost, a 15.5% experience rate will generate an approximate 64% reduction, but would not include any projected improvement post-v3.3 between 2015 and 2020.

Table 6: WEC Capital Costs and Experience Curve Effects

Sub-System	1st Unit Cost	Learning Rate	Cumulative Effect	nth Unit Cost
100 Hull Structure	$9,862,767	15.5%	66%	$3,390,637
200 Power Take Off*	$2,701,492	10.0%	49%	$1,560,802
300 Electric Plant	$1,064,100	10.0%	27%	$775,729
400 SCADA	$107,132	10.0%	27%	$78,099
500 Auxiliary Systems	$251,749	7.0%	20%	$202,496
600 Outfit & Furnishing	$56,510	2.5%	7%	$52,377
700 Mooring System	$1,736,150	10.0%	27%	$1,265,653
800 Electrical Collection System	$95,750	7.5%	21%	$403,040
	$15,875,650			$8,052,743

* Cost for DDP1 PTO is shown here. GP1 PTO 1st unit cost is estimated to be 22% higher, $3,295,820.

6.2 Installation Costs

WEC installation costs are estimated to be $200,000 per unit in 2020. This includes transportation to deployment site, unit load, deployment & tie-in, mooring installation, equipment & facilities, commissioning expenses.

6.3 Infrastructure Costs

The cost per WEC from the downstream umbilical connection to the grid interconnect is estimated to be $192,000/unit in 2020.

6.4 Failure rates

Prior to deployment of the WEC, components are assumed to have been culled for infant mortality through quality control (QC) inspections and shipyard testing.

6.5 Operations and Maintenance

CPower has devised a bottoms-up approach to calculate potential 2020 O&M costs, and no learning rate is applied. The methodology breaks O&M into onshore monitoring, visual inspections, planned on-site minor maintenance, unplanned on-site minor maintenance, unplanned in-port major maintenance, and in-port refitting. The cost of the maintenance procedures is a function of estimated vessel cost ($800-1,500/day), labor cost ($80/hour), material cost ($4,000-50,000/repair), days per repair (1-10), and number of annual occurrences. No special purpose O&M vessels are required. In-port costs also include a facilities charge of $1,000/day. Onshore monitoring is expected to be $4,000/WEC/yr.

For DDS1 WECs, 65% of the WECs in the array are expected to need unplanned in-port repairs each year. All WECs undergo periodic visual inspections, one planned minor repair and one unplanned maintenance procedure each year, but the high volume of unplanned in-port maintenance for the DDP1 generator is expected to remove the need for additional planned major and minor on-site repairs. This is because the normally-planned periodic maintenance will be performed during the unplanned in-port repairs. Expected improvements to DDPx will allow more on-site repairs and fewer unplanned in-port repairs.

Until more data is collected, it is assumed that the WEC will also be recovered once every five years for inspections, regular maintenance and refit prior to redeployment. Weather windows for recovery and deployment are each assumed to be 2-weeks and a 2-week refit period assumes replacement parts are readily available on-site. Given the frequency of in-port repairs, the in-port refitting has been set to equal the cost of an unplanned major repair.

6.6 Financial assumptions

6.6.1 Taxes

Effective tax rate is 39.6% as per DOE guidance. .

6.6.2 Depreciation

Service life is 20 years and MACRS deprecation duration is 5 years as per DOE guidance. No other financial incentives are included in the LCOE model.

6.6.3 Inflation

Inflation factor is 2.5% as per DOE guidance.

6.6.4 Discount Rate

The Discount Rate is 7% as per DOE guidance.

6.7 Soft Costs

Soft Costs are $893,000/MW as per NREL (2011) for offshore wind projects.

6.8 Output Improvement

Output improvement over time is calculated in the same manner as Experience Curve improvements. For DDS1, DP1 performance and efficiency is used for the 2020 WEC, and no changes in output are included in the Output Improvement rate of 12%. The Output Improvement is the result of performance increases from improvements due to currently-understood hydrodynamic improvements and advanced controls. The new v3.3 models showed a 63% improvement in output using linear damping. Additionally, 2020 WECs are assumed to have more advanced controls than the linear damping used in the 2015 DDS1 models. In its 2013-14 Phase I SBIR project on advanced controls, CPower determined that advanced controls would likely improve performance from 50-150%.[4] Combined with the v3.3 performance improvement and the advanced controls, future hydrodynamic improvements point to an aggregate improvement of 225%. This does not include improvements from unquantified technical advances.

Table 7: Output Improvement (Humboldt, CA)

Sub-System	1st Unit TAEP (MWh)	1st Unit AEP (MWh)	Improvement Rate	Cumulative Effect	nth Unit AEP (MWh)	Prior Installed Capacity (MW)
GS1	467	388	12%	225%	**873**	**30**
DDS1-p	547	499	12%	225%	**1,122**	**30**
DDS1-i	596	544	12%	225%	**1,223**	**30**
DDS1-f						
DDSx						

[4] *Wave Energy Converter Performance and Cost Optimization Through Novel Control Strategies,* March 2014

Table 7a: Output Improvement (Stonewall Bank, CA)

Sub-System	1st Unit TAEP (MWh)	1st Unit AEP (MWh)	Improvement Rate	Cumulative Effect	nth Unit AEP (MWh)	Prior Installed Capacity (MW)
GS1	585	486	12%	225%	**1,093**	**30**
DDS1-p	685	625	12%	225%	**1,406**	**30**
DDS1-i	743	678	12%	225%	**1,525**	**30**
DDS1-f						
DDSx						

6.9 Transmission losses

The LCOE model assumes relatively short distances from array to grid interconnect of 10 km, so expected loss within the model is negligible.

6.10 Array Capacity

Current DOE guidance calls for a project capable of producing 260,000 MWh/yr.

7 SPA AND LCOE ASSESSMENT

Results of the system assessment are described in this section. All figures in Table 8 System Improvement Metrics are for 2020 WECs at Stonewall Bank, OR as described above. All other Tables in this Section include data for Stonewall Bank, OR and Humboldt, CA.

Table 8: System Improvement Metrics

Baseline to Target	PWR		Availability		LCOE	
	Targeted	**Actual**	**Targeted**	**Actual**	**Targeted**	**Actual**
GS1 to DDS1-p	55%	48%	10%	11%	-28%	-25%
GS1 to DDS1-i	55%	60%	10%	11%	-28%	-31%
GS1 to DDS1-f	55%		10%		-28%	
GS1 to DDSx	78%		18%		-80%	

Table 9: Project Array LCOE

	LCOE ($/kWh)	
System - configuration	**Stonewall Bank, OR**	**Humboldt, CA**
GS1	.881	1.103
DDS1-p	.657	.827
DDS1-i	.607	.756
DDS1-f		
DDSx		

Table 10: 2020 WEC SPA and LCOE Metrics (Humboldt, CA)

System configuration	PWR (kW/ton)	Availability (%)	n^{th} Unit AEP (MWh)	ICC ($/kWh)	AOE ($/kWh)
GS1	0.17	83	**873**	1.002	.101
DDS1-p	0.25	92.5	**1,122**	.750	.077
DDS1-i	0.28	92.5	**1,223**	.690	.066
DDS1-f					
DDSx					

Table 10a: 2020 WEC SPA and LCOE Metrics (Stonewall Bank, OR)

System configuration	PWR (kW/ton)	Availability (%)	n^{th} Unit AEP (MWh)	ICC ($/kWh)	AOE ($/kWh)
GS1	0.21	83	**1,093**	.800	.081
DDS1-p	0.32	92.5	**1,406**	.599	.058
DDS1-i	0.34	92.5	**1,525**	.554	.053
DDS1-f					
DDSx					

8 PRE-PROJECT SYSTEM SPA AND LCOE ASSESSMENT

Pre-project system specifications and methods are described in this section. See section 2.1 for system definitions.

8.1 GS1 system specification

Table 11: GS1 system specification

Parameter	units	Specification
PTO Availability	%	83
WEC active mass	metric tons	582.5
WEC dry mass	metric tons	914.6
WEC displacement	metric tons	1,200.8
PTO mass	metric tons	67
Rated Capacity	kW	370
Capacity Factor	%	33.7 = 1,093,000/(8,760*370)
efficiency	%	66
Max Torque	MNm	1.5
Diameter	m	Not relevant
Length	m	Not relevant

8.2 GS1 PWR

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

$$PWR\ active = \frac{370\ kw\ x\ 0.337}{582.5\ (metric\ tons)} = \ 0.21\ \frac{kW}{ton}$$

$$PWR\ dry = \frac{370\ kw\ x\ 0.337}{914.6\ metric\ tons} = 0.14\frac{kW}{ton}$$

8.3 DDS1-p system specification

To establish the initial pre-project AEP on the DDS1-p WEC, CPower performed time-domain modeling as described in Attachment 1 and reported in Attachment 3. For the GS1 system, CPower will use assumptions on efficiency, inertia and availability to estimate its AEP.

CPwr will not use time-domain models on system GS1 (DDS1 with GS1 PTO). The GS1 PTO mass is heavier than the DDS1-p PTO, thus with more mass in the nacelle of the WEC, this forces less ballast to be used in the damper, creating a higher center of gravity (CG) in the GS1 WEC. WEC modeling on system DDS1 has identified that a higher CG causes a reduction in energy production that is linear with an upward change in CG; for this reason, system GS1 WEC power extraction is reduced by 5.7% with respect to DDS1.

Table 12: DDS1-p system specification

Parameter	units	Specification
PTO Availability	%	92.5
WEC active mass	metric tons	506.9
WEC dry mass	metric tons	914.6
WEC displacement	metric tons	1,200.8
PTO mass	metric tons	28.2
Rated Capacity	kW	370
Capacity Factor	%	43.4 = 1,406,000/(8,760*370)
inertia	kgm^2	112,046
efficiency	%	72
max Torque	MNm	1.5
Diameter	m	9.0
Length	m	0.86
air gap	mm	4

8.4 DDS1-p PWR

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

$$PWR\ active = \frac{370\ kw\ x\ 0.434}{506.9\ (metric\ tons)} = \ 0.32\ \frac{kW}{ton}$$

$$PWR\ dry = \frac{370\ kw\ x\ 0.434}{914.6\ metric\ tons} = 0.18\frac{kW}{ton}$$

8.5 DDS1-p Availability

DDS1-p Availability is calculated in Attachment 6 "*DDS1-p MTBF MTTR Service life PTO V2.xlsx*"

9 INTERMEDIATE SYSTEM SPA AND LCOE ASSESSMENT

To be completed in preparation for Go/No-Go. Intermediate project system specifications and methods are described in this section.

9.1 DDS1-i system specification

Table 13: DDS1-i system specification

Parameter	units	Specification
PTO Availability	%	92.5
WEC active mass	metric tons	506.9
WEC dry mass	metric tons	914.6
WEC displacement	metric tons	1,200.8
PTO mass	metric tons	28.2
Rated Capacity	kW	391
Capacity Factor	%	44.5 = 1,525,000/(8,760*391)
inertia	kgm^2	112,046
efficiency	%	78
max Torque	MNm	1.5
Diameter	m	9.0
Length	m	0.86
air gap	mm	4

9.2 DDS1-i PWR

$$PWR = \frac{Rated\ Capacity\ (kw)\ x\ CapacityFactor}{Weight\ in\ Air\ (metric\ tons)}$$

$$PWR\ active = \frac{391\ kw\ x\ 0.471}{506.9\ (metric\ tons)} = 0.34\ \frac{kW}{ton}$$

$$PWR\ dry = \frac{391\ kw\ x\ 0.471}{914.6\ metric\ tons} = 0.19\frac{kW}{ton}$$

9.3 DDS1-i Availability

DDS1-i availability is calculated in Attachment 7 "*DDS1-i MTBF MTTR Service life PTO V2.xlsx*"

10 FINAL SYSTEM DESIGN SPA AND LCOE ASSESSMENT

To be completed along with final reporting. Final project system specifications and methods are described in this section.

GLOSSARY

AEP	Annual Energy Production
AOE	Annual Operating Expense
CAPEX	Capital Expense
CBS	Cost Breakdown Structure
CDT	Component Down Time
CPower	Columbia Power Technologies
DT	Down Time
DDP1	Project direct-drive PTO module
DDPx	Next-generation direct-drive PTO module
DDR	Direct-Drive Rotary
DDS1	Targeted initial WEC [StingRAY with DDP1]
DDS1-i	Targeted initial WEC [understood at GNG stage]
DDS1-f	Targeted initial WEC [understood at Project finish]
DDS1-p	Targeted initial WEC [understood pre-Project]
DDSx	2020 WEC [StingRAY with DDPx]
DOE	Department of Energy
FCR	Fixed Charge Rate
FOA	Funding Opportunity Announcement
GNG	Go/No-Go decision point
GP1	Baseline geared PTO module
GS1	Baseline WEC
LCOE	Levelized Cost of Energy
MACRS	Modified Accelerated Cost Recovery System
MHK	Marine HydroKinetic
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NETL	National Energy Technology Laboratory
O&M	Operating & Maintenance
PMG	Permanent Magnet Generator
Project LandRAY	Project DE-EE0006399
PTO	Power Take Off
PWR	Power-to-Weight Ratio
QC	Quality Control
RDT	Recovery and Deployment Time
SDT	System Down Time
SOPO	Statement of Project Objectives
SPA	System Performance Advancement
TAEP	Transmitted Annual Energy Production
WEC	Wave Energy Converter

PWR	Power-to-Weight Ratio
QC	Quality Control
RDT	Recovery and Deployment Time
SDT	System Down Time
SPA	System Performance Advancement
TAEP	Transmitted Annual Energy Production
WEC	Wave Energy Converter

ATTACHMENTS

Attachment 1 – Energy Production Assessment for DOE LCOE and SPA Reporting

Attachment 2 – DDS1-p-BOM Master.xlsm

Attachment 3 – DDS1-p TAEP calculations

Attachment 4 – DDS1-i TAEP calculations

Attachment 5 – Final TAEP calculations

Attachment 6 – DDS1-p MTBF MTTR Service life PTO V2.xlsx

Attachment 7 – DDS1-i MTBF MTTR Service life PTO V2.xlsx